Investigating Distance Knowledge Using Virtual Environments

Petra Jansen-Osmann and Bettina Berendt

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INVESTIGATING DISTANCE KNOWLEDGE USING VIRTUAL ENVIRONMENTS

PETRA JANSEN-OSMANN *holds a master's degree in biological and social anthropology and psychology from Johannes-Gutenberg-University Mainz and a Ph.D. in cognitive psychology from Gerhard-Mercator-University Duisburg. She is currently a research fellow at the Institute of Experimental Psychology at Heinrich-Heine-University Düsseldorf, Germany. Her research is concerned with human spatial cognition and behavior in natural and virtual environments and motor development.*

BETTINA BERENDT *holds master's degrees in business economics, economics, and artificial intelligence from Berlin, Cambridge, and Edinburgh Universities, and a Ph.D. in computer science/cognitive science from Hamburg University. She is currently an assistant professor at the Institute of Information Systems at Humboldt University Berlin. Her research focuses on computational and psychological methods for analyzing interaction with computers, in particular uses of World Wide Web resources and interaction with computer visualizations.*

ABSTRACT: Computer-simulated three-dimensional environments have become a popular tool in spatial cognition research. One way of demonstrating their usefulness is to replicate experimental results obtained in physical spaces. Two experiments investigated the role of environmental features in distance cognition, following Sadalla and Magel. Their participants explored routes marked with tape on the floor through active walking. Results showed that a higher number of turns along a route increased the estimated length of that route. In the authors' experiments, participants had to explore the routes in a desktop virtual environment. Experiment 1 employed ratio estimation and drawing methods and replicated Sadalla and Magel's findings. Experiment 2 employed a reproduction method, and extends the results by showing that relative to physical distance, the route with fewer turns was underestimated, while the

AUTHORS' NOTE: *Please send correspondence to Dr. Petra Jansen-Osmann, Heinrich Heine University Düsseldorf, Institute of Experimental Psychology, General Psychology, Universitätsstr.1, D-40225 Düsseldorf; phone: +49 211 8112270; fax: +49 211 8115037; e-mail: petra.jansen-osmann@uni-duesseldorf.de.*

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route with more turns was overestimated. The results show that desktop virtual environments are a valid and economic research tool.

People can acquire spatial knowledge by traveling through environments, or by using maps, photographs, verbal descriptions, and more recently, virtual environments. Virtual environments are increasingly being used in research on spatial cognition. They fall into two categories: In desktop systems, one sees simulated three-dimensional environments projected onto the two-dimensional screen of a normal desktop computer. Immersive display systems employ special output devices like head-mounted displays and increase the impression of being "immersed" in the virtual environment by largely preventing the perception of external stimuli from the "real" environment. Both desktop and immersive display systems are adequate for the simulation of spatial environments: Spatial relations can be varied quickly and economically, user action in the simulated environment is self-determined, and real as well as fictional environments can be simulated (cf. Goldin & Thorndyke, 1982, for requirements on a simulation medium). The use of virtual environments in research on spatial cognition includes the investigation of navigation behavior in these environments (Darken & Silbert, 1996; Ruddle, Payne, & Jones, 1999) and of processes in spatial problem solving when proprioceptive information is missing (e.g., the path integration tasks investigated by May & Klatzky, 2000). In virtual environments, people can acquire knowledge about directions (Albert, Rensink, & Beusmans, 1999) and about distances (Jansen-Osmann, 1999; Wartenberg, May, & Péruch, 1998), and they can form both route and survey knowledge (Bliss, Tidwell, & Guest, 1997; Gillner & Mallot, 1998). The importance of using virtual environments is increasingly being perceived, not least because of the economical and realistic design of laboratory experiments (Péruch, Gaunet, Thinus-Blanc, & Loomis, 2000).

One way of evaluating virtual environments is to try to replicate results obtained in laboratory experiments carried out in physical spaces. For example, Ruddle, Payne, and Jones (1997) could replicate, in virtual environments, the results on direction and distance knowledge obtained by Thorndyke and Hayes-Roth (1982) in real-world settings.

The experiments reported here tested, in a virtual environment, the hypothesis of Sadalla and Magel (1980) that the number of turns in a route influences the estimated length of that route (i.e., the distance between the route's start point and end point). Sadalla and Magel could show that a route that enforced a change in direction more often—in this case, by 7 right-angle turns—was estimated as longer than a route of the same physical length containing only 2 right-angle turns. This result was independent of whether participants walked the route once or three times during the learning phase, and independent of the time needed to learn the routes. In a second experiment, the authors showed that the number of turns did not influence the estimated duration of the routes walked. In a third experiment, it was shown that a route with 5 turns was estimated as longer than a route of the same length with 3 turns, and that this was independent of the physical distance between the start and the goal of the pair of routes to be compared. Three possible explanations were discussed: the storage hypothesis, the scaling hypothesis, and the effort hypothesis. The storage hypothesis is based on the "information storage model" proposed by Milgram (1973): A strongly segmented route contains more information, necessitates more information processing activity, and leads to a larger amount of stored information. Participants estimated complex routes as longer because these contained more information and therefore required the storing of more information. (Sadalla, Staplin, and Burroughs [1979] examined the storage hypothesis in more detail and provided an extended analysis of the role of information retrieval in the estimation of route distances.)

The scaling hypothesis assumes that the right-angle turns divide the route into segments, and that the perceived lengths of the single segments are mentally added to estimate the whole route. Of two routes of the same physical length, the one with more turns has shorter segments. In the estimation of environmental distances (i.e., distances in large-scale spaces), larger distances tend to be underestimated relative to their physical length, whereas smaller distances tend to be overestimated (or, larger distances are underestimated more or overestimated less than smaller distances) (Dainoff, Miskie, Wilson, & Crane, 1974). Therefore, the longer segments of the route with fewer turns are underestimated relative to the shorter segments of the route with more turns. When these "compressed" segments are added to estimate the length of the whole route, the route with fewer turns is thus underestimated relative to the route with more turns. The effort hypothesis assumes that participants estimate the length of a walked route based on the effort expended in walking. Walking complex routes is assumed to be associated with a subjectively higher effort than walking less complex routes; so complex routes are estimated as longer than less complex ones.

The effect found by Sadalla and Magel has been called into question by a later study by Herman, Norton, and Klein (1986). Investigating the influence of different numbers of turns on the route distance estimations made by children, the authors found no effect. One of their conclusions was that "future research examining this effect must be conducted under conditions in which the events encountered along a path are strictly controlled" (p. 533).

We expect that virtual environments are adequate simulation media for spatial environments. They have the additional advantage that the objects or events encountered along a path can be strictly controlled. Therefore, Experiment 1 was carried out with the aim of replicating the result that a route with more turns is estimated as longer than a route of the same physical length with fewer turns. The subsequent Experiment 2 employed a reproduction technique to investigate the relationship between estimated and physical distances of the routes.

EXPERIMENT 1

METHOD

Participants

Twenty students of Gerhard-Mercator-University Duisburg volunteered for Experiment 1—11 male (average age 27.18 years) and 9 female (average age 25.33 years).

Materials

Two routes were simulated with the software Superscape VRT 4.00. They consisted of a set of corridors: a route A of 200 units length and containing 2 turns, a route B of 200 units length and containing 7 turns, and a straight route C of 100 units length. The survey views of routes A through C were identical to those of the original study by Sadalla and Magel (1980) shown in Figure 1.

In contrast to the original study, the routes had floor tiles (see Figure 2). This was done to provide more texture in the optical flow, contributing to the impression of spatial movement. The floor tiles were small, so they could not be counted during navigation. (Counting regularly occurring environmental features is a possible heuristic for distance estimation; giving participants this opportunity could bias the results, e.g., Montello, 1997.)

Participants were seated in front of a 17-inch monitor and learned the routes by active navigation with a joystick.

In the test phase, participants received a protocol sheet. The sheet contained a horizontal line; on this line, route C was shown with start point X and goal point Y. The length of route C was about a third of the total length of the line.

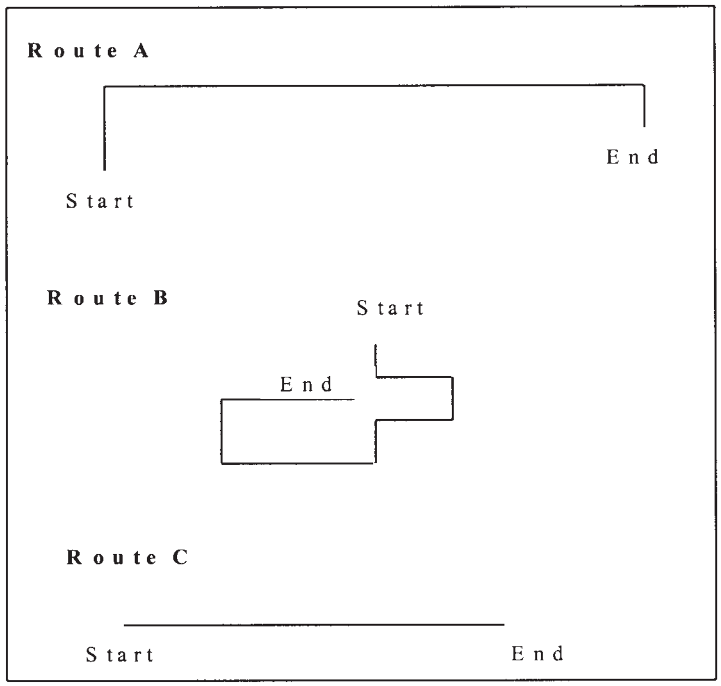

Figure 1: Overview of the Routes (Experiment 1)

Procedure

Participants were tested in single sessions lasting about 20 minutes each. First, participants—who were already familiar with the use of the joystick—had the opportunity to familiarize themselves with the joystick's rotation and translation settings. Participants were instructed to explore the three routes A to C. Each route was explored forward and then backward once. The order of the exploration of routes A and B was balanced; C was always explored last. The time needed for walking the routes was registered.

The test phase consisted of two parts: First, participants were asked to mark the lengths of routes A and B in relation to route C on the protocol sheet, starting from the start point X. Then, participants were asked to draw the routes A and B on a white A4 paper sheet. The drawn lengths were measured in millimeters.

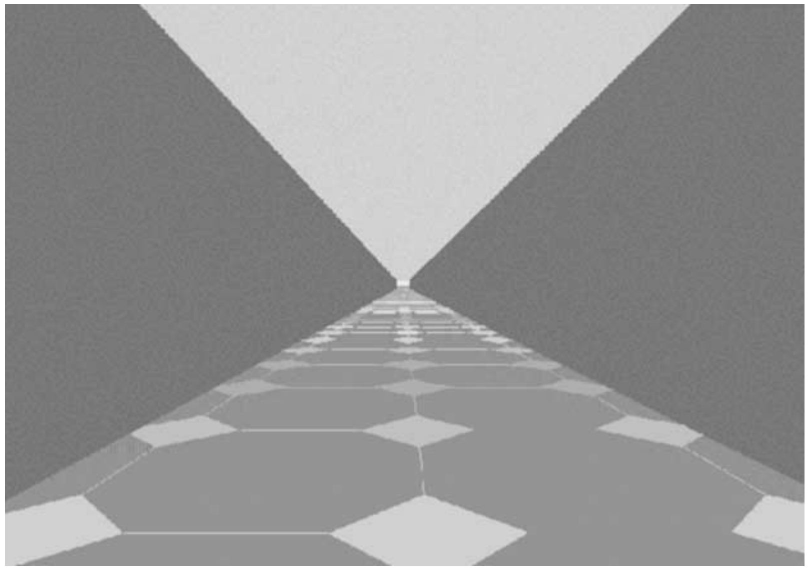

Figure 2: A Typical Corridor of the Virtual Routes

Experimental Design

The factor "kind of route" was manipulated within subjects (route A with 2 turns vs. route B with 7 turns). Dependent variables were length of routes estimated via ratio-estimation (measured in millimeters), length of routes estimated via route drawing (measured in millimeters), number of turns in the drawing, kinds of turns in the drawing (a sequence of "left" and/or "right"), and time needed to explore the routes.

RESULTS

Figure 3 shows the mean values and standard errors of the route lengths estimated via ratio estimation. It also shows the corresponding mean values found by Sadalla and Magel (1980).

Figure 3 shows that route A with 2 turns was estimated as shorter than route B with 7 turns (route A: $\bar{x}$ = 149.25 mm, σ = 11.08; route B: $\bar{x}$ = 175.6 mm, σ = 9.86). The difference was significant ($t_{(19)} = 2.94$, $p < .005$).

Figure 4 shows the mean values and standard errors of the drawn route lengths. It also shows the corresponding mean values found by Sadalla and Magel (1980).

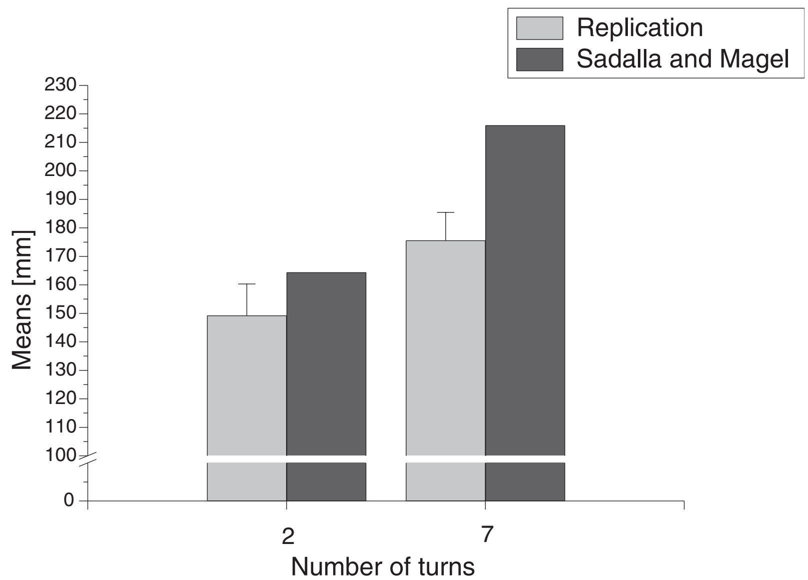

Figure 3: Means of Estimated Route Length in Experiment 1 (Ratio-Estimation Technique)

NOTE: Vertical bars indicate standard errors.

Figure 4 shows that route A was estimated as shorter than route B (route A: $\bar{x}$ = 130.25 mm, σ = 14.65; route B: $\bar{x}$ = 183.85 mm, σ = 16.16). The difference was significant ($t_{(19)} = 2.87$, $p = .005$).

Analysis of the number of turns in the drawings showed that, on average, the number of turns was remembered quite accurately. Route A containing 2 turns was drawn with a mean of 2.3 turns (σ = .32, min. = 0, max. = 8), and route B containing 7 turns was drawn with a mean of 7.4 turns (σ = .6, min. = 4, max. = 14). Seventy percent of participants estimated the number of turns of route A correctly, compared to only 20% for route B. In the analysis of the directions of turns in the drawings, only those drawings were considered that contained the right number of turns. Of these, 85.7%, which amounted to 60% of all participants, had reproduced the directions of turns correctly for route A. No participant reproduced the directions of turns correctly for route B.

The order of presentation of routes did not influence the distance estimates. Also, no influence of gender was found.

The times needed to explore the routes A and B differed significantly (route A: $\bar{x}$ = 55.21 sec, σ = .22; route B: $\bar{x}$ = 57.14 sec, σ = .52; $t_{(19)} = 4.03$, $p = .001$). This difference appears to be a methodological artifact because the

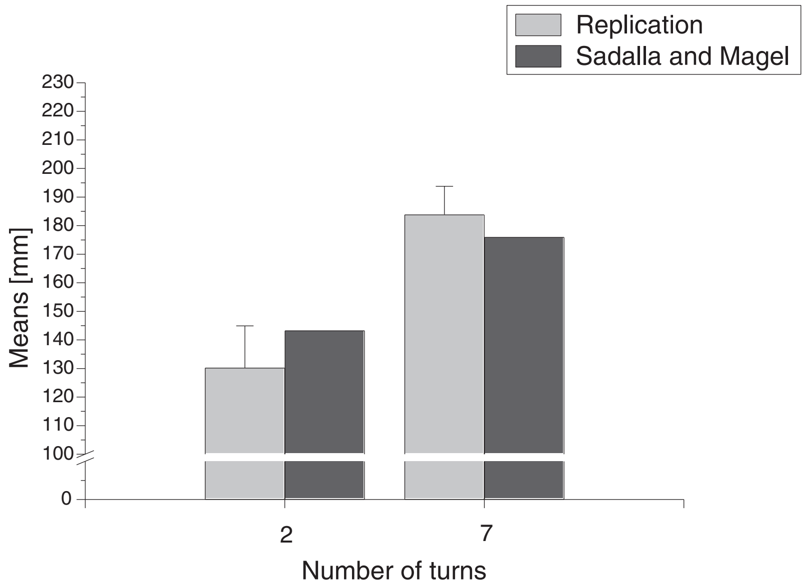

Figure 4: Means of Estimated Route Length in Experiment 1 (Drawing Technique)
NOTE: Vertical bars indicate standard errors.

rotation speed set for the joystick caused the exploration of the route with more turns to take longer. To exclude the influence of this artifact, the relationship between the distance estimates and the exploration times for the two routes was investigated. If the relationship between the distance estimate of route B and that of route A corresponded to the relationship between the exploration time for B and for A, the overestimation of B relative to A could not be traced exclusively to the different numbers of turns.

To investigate this possibility, the differences between the estimated lengths of A and B were correlated with the differences between exploration times of A and B. No relation was found (distance estimates obtained by ratio estimation: $r = .19$, $p = .416$; distance estimates obtained by drawing: $r = .16$, $p = .494$).

DISCUSSION

The results confirm the expectations formulated above: In virtual environments too, a route with a higher number of turns is overestimated relative to a route of the same physical length with fewer turns.

In contrast to the original study by Sadalla and Magel (1980), a significant difference was found in the times needed to explore the routes. However, this difference was not correlated with the differences in distance estimates. So the number of turns, and not the time needed for walking, served as a heuristic for estimating distance (cf. Montello, 1995, 1997).

Not only the time needed for walking but also effort can be excluded as an influence on the estimation of distances. All participants were familiar with the use of the joystick, and they experienced no difference in the effort needed to traverse the route with 2 versus 7 turns. Therefore, the effort hypothesis need not be considered further to explain the results. A statement about the validity of the scaling hypothesis cannot be made on the basis of these data. Participants were not able to draw the route with 7 turns correctly, therefore no statement about the compression of the longer segments of route A relative to the shorter segments of route B is possible. Given that participants estimated the number of turns of both routes approximately correctly, and assuming that a path with more turns contains more information, the results support the storage hypothesis: Participants estimated the more complex route B as longer because they had stored more information.

In the experiment, two different methods of distance estimation were used: ratio estimation and reconstruction by drawing. Both methods require scale translations and the representation in another medium. Both methods have the drawback that the distances estimated can only be compared with one another. Statements concerning overestimation or underestimation with respect to the physical lengths of the routes cannot be made. Therefore, in a second experiment, a reproduction method was employed that tested spatial knowledge in the space where it was acquired.

EXPERIMENT 2

METHOD

Participants

Fifteen students of Gerhard-Mercator-University Duisburg, none of whom had participated in Experiment 1, volunteered in Experiment 2—13 male (average age 27.77 years) and 2 female (average age 26 years).

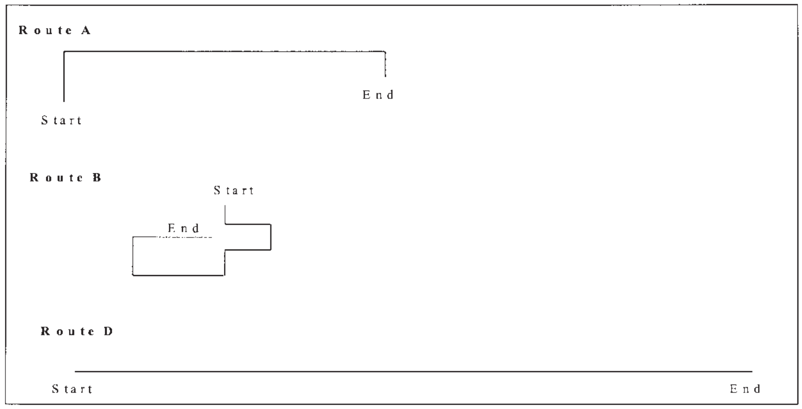

Figure 5: Overview of the Routes (Experiment 2)

Materials

The materials were routes A and B from Experiment 1, and a route D of 300 units length. Figure 5 shows routes A, B, and D.

Again, participants were seated in front of a 17-inch monitor and learned the routes by active navigation with a joystick.

Procedure

Participants were tested in single sessions lasting about 20 minutes each. The learning phase was the same as in Experiment 1.

Participants were instructed to explore the routes A and B as in Experiment 1; the order of A and B was balanced.

In the test phase, participants were asked to walk route D until they thought they had walked the lengths of A and B: They were asked to press the Escape key when they thought they had walked the shorter route's length, then, if necessary, proceed and again press the Escape key when they thought they had walked the remaining length of the longer route. They were told that this was designed to measure the estimated distances of the routes.

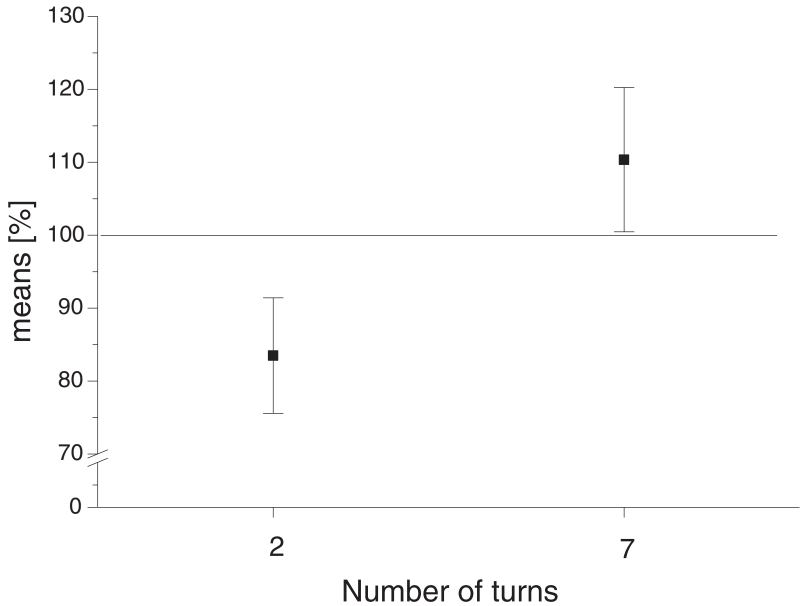

Figure 6: Means and Standard Error of Estimated Route Lengths Relative to Physical Route Length in Experiment 2 (Reproduction Technique)

Experimental Design

The factor "kind of route" was manipulated within subjects (route A with 2 turns vs. route B with 7 turns). The dependent variable was the length of the routes estimated via reproduction (measured in the software's internal units).

RESULTS

The estimated lengths were transformed into percentages of the respective route's "physical" length (the length in the software's internal units). Figure 6 shows the mean values and standard errors of the estimated route lengths compared to their physical lengths.

Figure 6 shows that route A with 2 turns was estimated as shorter than route B with 7 turns. The figure shows that the length of route A was underestimated relative to physical length, whereas the length of route B was overestimated (route A: $\bar{x}$ = 83.5%, σ = 7.92; route B: $\bar{x}$ = 110.35%, σ = 9.35).

In this experiment too, times needed to explore the routes differed significantly ($t_{(14)} = 4.64$, $p < .001$ with route A: $\bar{x}$ = 55.24 sec, σ = .28; route B: $\bar{x}$ =

58.24 sec, $\sigma = .74$). No relation was found between the different distance estimates and the time needed for exploration ($r = .01$, $p = .971$).

DISCUSSION

Using a reproduction method, the same finding was repeated: A route with a higher number of turns was overestimated relative to a route of the same physical length with fewer turns. Also, the reproduction method showed that the route with fewer turns was underestimated relative to its physical length, whereas the route with more turns was overestimated relative to its physical length.

The reproduction method has not been employed much in previous research because the large distances have made it quite uneconomical in environmental spaces (cf. Montello, 1991). Virtual reality (VR) techniques, however, now offer the possibility to directly measure spatial behavior also for large distances and to make statements about the relations between estimated and physical distances. This contrasts with other methods, where estimates can only be compared with one another (cf. Montello, 1991). When VR techniques are used, reproduction methods become economical. This extends the ecological validity of laboratory experiments.

GENERAL DISCUSSION

In spite of a lack of proprioceptive information, the results of these experiments replicate and extend the results of Sadalla and Magel (1980). In virtual as in physical environments, the estimation of distance is distorted by a route's environmental features (in this case, turns). This is in accordance with a recent study by Belingrad and Péruch (2000) on the influence of different spatial structures on knowledge about directions and distances in a virtual environment: In a structure-free environment, in which objects could be seen and reached in a straight line from any viewpoint, the errors in distance estimation were less than in a much more structured environment, in which walls precluded objects from being visible from a single viewpoint and from being reachable along a straight line. In this structured environment, distances had to be inferred, and this led to a "cognitive distortion."

Knowledge about a spatial relation can be based primarily on perception, or it can require a sizeable amount of cognitive processing, an integration of various information elements. This integration requires inferences to be made, and these are often based on heuristics. A typical example of the first case is the knowledge about the distance between two places that are visible from each other. A typical example of the second case is the knowledge about the distance between two places in large-scale spaces, places that are far apart and not visible from one another. These different kinds of knowledge are often termed "perceptual" and "cognitive" components (cf. Montello, 1991, 1997, for a description and critical discussion). The question needs to be asked whether (desktop) virtual environments can be used only to investigate cognitive components. Evidence in favor of this view comes from the results of Richardson, Montello, and Hegarty (1999), who compared spatial knowledge acquired in a real environment with knowledge acquired in a desktop virtual environment. They found no differences in the complex task of estimating route distances. However, differences can be found in the investigation of perceptual components, as in path integration tasks. The lack of proprioceptive information in a desktop virtual environment led to a larger error in direction estimates than the lack of visual information when participants were blindfolded (Wartenberg, May, & Péruch, 1998; for a survey, see Klatzky, 1998).

In conclusion, virtual environments appear to be adequate instruments for the investigation of cognitive components of the processing of spatial information. The advantage of the use of virtual environments is that exploration of a space is active, an important characteristic of the acquisition of route knowledge in everyday situations. In addition, environments can be simulated in little time, spatial configurations can be presented in different ways, including a free choice of level of detail, and an easy variability of spatial relations. Furthermore, the VR technique permits the creation of environments of varying complexity, provides continuous measurements during navigation, and affords the control of the number, position, and nature of landmarks. The use of virtual environments in research avoids constraining limits of real-world experimental situations (Péruch, Gaunet, Thinus-Blanc, & Loomis, 2000).

In summary, these results illustrate that the cognitive components of the processing of spatial information can be investigated in desktop virtual environments. Knowing that, we can go further on to use these environments for the investigation of spatial processes. These studies are just beginning but appear promising. For example, in our own work in virtual environments, we could show that distance estimation is more influenced by the number of features than by the structure of the route (Berendt & Jansen-Osmann, 1997; Jansen-Osmann, 2001). More and more complex and realistic virtual environments will continue to improve possibilities for the investigation of spatial knowledge.

This may have widespread implications for the use of VR technology across diverse areas (for a detailed description, see http://www.hitl.washington.edu/projects/knowledge_base/research.html), with many applications involving large-scale environments. Application areas include entertainment ranging from 3D computer games for primary school children to the use of head-mounted displays to create virtual scenery in theatre performances. In military research, VR allows maneuvers to be carried out in simulated spaces (Bauer, 1996). VR is a standard instrument in engineering, architecture, and design. It is possible to "walk through" rooms created by VR, such that architectural details can be experienced from the perspective of those who will later move around the constructed rooms. This is useful, for example, for the construction of buildings suitable for wheelchair users (cf. Stredney, Carlson, Swan, & Blostein, 1995).

In education and training, VR first appeared in the flight simulators used in pilot training. It is now employed in other areas from language learning to the education of medical students with virtual corpses (Trueman, 1996; Zohrab, 1996). Museums employ VR to create interactive expositions (cf. Völter, 1995; recent examples include LeMO, 2001, and the "Virtual Smithsonian," 2001). Museums, as well as other agencies such as tourist boards, may see the need to simulate environments that exist but cannot be visited "in the real world." Such environments can be reconstructed historical buildings (e.g., the medieval palace "Kaiserpfalz," see Strothotte, Masuch, & Isenberg, 1999) or cities (e.g., "Virtual Tuebingen," see Van Veen, Distler, Braun, & Bülthoff, 1998).

As the results reported in this article show, acquiring knowledge about spatial relations in these environments should be similar to learning real environments. This will make these programs widely useful, for example, for educational purposes.

REFERENCES

Albert, W. S., Rensink, R. A., & Beusmanns, J. (1999). Learning relative directions between landmarks in a desktop virtual environment. *Spatial Cognition and Computation*, *1*, 131-144.

Bauer, Ch. (1996). *Nutzenorientierter Einsatz von Virtual Reality im Unternehmen* [Useful application of virtual reality in a business establishment]. Munich, Germany: Computerwoche Verlag.

Belingrad, L., & Péruch, P. (2000). Mental representations and the spatial structure of virtual environments. *Environment and Behavior*, *32*, 427-442.

Berendt, B., & Jansen-Osmann, P. (1997). Feature accumulation and route structuring in distance estimations—An interdisciplinary approach. In S. Hirtle & A. Frank (Eds.), *Spatial information theory. COSIT 1997* (pp. 279-295). Berlin, Germany: Springer.

Bliss, J., Tidwell, P., & Guest, M. (1997). The effectiveness of virtual reality for administering spatial navigation training to firefighters. *Presence*, *6*, 73-86.

Dainoff, M. J., Miskie, D. K., Wilson, C., & Crane, P. (1974). Psychophysical measurement of environmental distance. In D. H. Carson (Ed.), *Man-environment interactions: Evaluations and associations (EDRA 5 Proceedings)* (pp. 1-20). Milwaukee, WI: D. H. Carson.

Darken, R. P., & Silbert, J. L. (1996). Navigating large virtual spaces. *International Journal of Human-Computer Interaction*, *8*, 49-71.

Gillner, S., & Mallot, H. (1998). Navigation and acquisition of spatial knowledge in a virtual maze. *Journal of Cognitive Neuroscience*, *10*, 445-463.

Goldin, S. E., & Thorndyke, P. W. (1982). Simulating navigation for spatial knowledge acquisition. *Human Factors*, *24*, 457-471.

Herman, J. F., Norton, L. M., & Klein, C. A. (1986). Children's distance estimates in a large-scale environment: A search for the route angularity effect. *Environment and Behavior*, *18*, 533-558.

Jansen-Osmann, P. (1999). *Kognition von Distanzen: Laborexperimentelle Untersuchungen in virtuellen Umgebungen* [Distance cognition: Experimental investigations in virtual environments]. Ph.D. dissertation, Gerhard-Mercator-Universität Duisburg, Germany. Retrieved February 5, 2001 from http://www.ub.uni-duisburg.de/diss/diss9906/

Jansen-Osmann, P. (2001). Der Einfluß der Gestaltung einer Route auf die Distanzkognition [The influence of environmental features of a route on distance knowledge]. *Zeitschrift für Experimentelle Psychologie, 48,* 327-338.

Klatzky, R. L. (1998). Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections. In C. Freksa, C. Habel, & K. F. Wender (Eds.), *Spatial cognition: An interdisciplinary approach to representing and processing spatial knowledge* (pp. 1-18). Berlin, Germany: Springer.

LeMO. (2001). *LeMO, "the living museum online*." Retrieved February 5, 2001, from http://www.dhm.de/lemo

May, M., & Klatzky, R. (2000). Path integration while ignoring irrelevant movement. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*, 169-186.

Milgram, S. (1973). Introduction. In W. H. Ittelson (Ed.), *Environment and cognition* (pp. 21-27). New York: Seminary Press.

Montello, D. R. (1991). The measurement of cognitive distance: Methods and construct validity. *Journal of Environmental Psychology*, *11*, 101-122.

Montello, D. R. (1995). *The perception and cognition of environmental distance: Processes and knowledge source*. Unpublished manuscript. University of California at Santa Barbara.

Montello, D. R. (1997). The perception and cognition of environmental distance: Direct sources of information. In S. C. Hirtle & A. U. Frank (Eds.), *Spatial information theory: A theoretical basis for GIS* (pp. 297-311). Berlin, Germany: Springer-Verlag, Lecture Notes in Computer Science 1329.

Péruch, P., Gaunet, F., Thinus-Blanc, C., & Loomis, J. (2000). Understanding and learning virtual spaces. In R. M. Kitchin & S. Freundschuh (Eds.), *Cognitive mapping: Past, present and future* (pp. 108-124). London: Routledge.

Richardson, A. E., Montello, D. R., & Hegarty, M. (1999). Spatial knowledge acquisition from maps and from navigation in real and virtual environments. *Memory and Cognition*, *27*, 741-750.

Ruddle, R. A., Payne, St. J., & Jones, D. M. (1997). Navigating buildings in desk-top virtual environments: Experimental investigations using extended navigational experience. *Journal of Experimental Psychology: Applied*, *3*, 143-159.

Ruddle, R. A., Payne, St. J., & Jones, D. M. (1999). The effect of maps on navigation and search strategies in very-large-scale virtual environments. *Journal of Experimental Psychology: Applied*, *5*, 54-75.

Sadalla, E. K., & Magel, S. G. (1980). The perception of traversed distance. *Environment and Behavior*, *12*, 65-79.

Sadalla, E. K., Staplin, L. J., & Burroughs, W. J. (1979). Retrieval processes in distance cognition. *Memory & Cognition*, *7*, 291-296.

Stredney, D., Carlson, W., Swan, J. E., II, & Blostein, B. (1995). The determination of environmental accessibility and ADA compliance through virtual wheelchair simulation. *Presence*, *4*, 297-305.

Strothotte, Th., Masuch, M., & Isenberg, T. (1999). Visualizing knowledge about virtual reconstructions of ancient architecture. In *Proceedings Computer Graphics International* (pp. 36-43). The Computer Graphics Society, IEEE Computer Society. See also http://isg.www.cs.uni-magdeburg.de/projects/pfalz [February 5, 2001].

Thorndyke, P. W., & Hayes-Roth, B. (1982). Differences in spatial knowledge acquisition from maps and navigation. *Cognitive Psychology*, *14*, 560-589.

Trueman, B. (1996). Quick Time VR and English as a second language. *VR in the Schools*, *1*, 13.

Van Veen, H.A.H.C., Distler, H. K., Braun, S. J., & Bülthoff, H. H. (1998). Navigating through a virtual city: Using virtual reality technology to study human action and perception. *Future Generation Computer Systems*, *14*, 231-242. See also http://www.kyb.tuebingen.mpg.de/bu/projects/vrtueb

Virtual Smithsonian. (2001). Retrieved February 5, 2001, from http://2k.si.edu

Völter, S. (1995). *Virtual Reality in der Medizin* [Virtual reality in medicine]. Mannheim, Germany: Gesi.

Wartenberg, F., May, M., & Péruch, P. (1998). Spatial orientation in virtual environments: Background considerations and experiments. In C. Freksa, C. Habel, & K. F. Wender (Eds.), *Spatial cognition: An interdisciplinary approach to representing and processing spatial knowledge* (pp. 469-489). Berlin, Germany: Springer.

Zohrab, P. (1996). Virtual language and culture reality. *VR in the Schools*, *1*, 14-15.